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The "Spring Predictability Barrier" Phenomenon of ENSO Predictions Generated with the FGOALS-g Model

WEI Chao[1,2] and DUAN Wan-Suo[1]

[1] *LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China*
[2] *Graduate University of Chinese Academy of Sciences, Beijing 100049, China*

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Abstract Using the sea surface temperature (SST) predicted for the equatorial Pacific Ocean by the Flexible Global Ocean-Atmosphere-Land System Model-gamil (FGOALS-g), an analysis of the prediction errors was performed for the seasonally dependent predictability of SST anomalies both for neutral years and for the growth/decay phase of El Niño/La Niña events. The study results indicated that for the SST predictions relating to the growth phase and the decay phase of El Niño events, the prediction errors have a seasonally dependent evolution. The largest increase in errors occurred in the spring season, which indicates that a prominent spring predictability barrier (SPB) occurs during an El Niño-Southern Oscillation (ENSO) warming episode. Furthermore, the SPB associated with the growth-phase prediction is more prominent than that associated with the decay-phase prediction. However, for the neutral years and for the growth and decay phases of La Niña events, the SPB phenomenon was less prominent. These results indicate that the SPB phenomenon depends extensively on the ENSO events themselves. In particular, the SPB depends on the phases of the ENSO events. These results may provide useful knowledge for improving ENSO forecasting.

Keywords: ENSO event, spring predictability barrier, prediction error, predictability

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1 Introduction

The El Niño-Southern Oscillation (ENSO) cycle is a short-term climate variation that occurs mainly in the tropical Pacific ocean and ENSO's serious impacts on weather and climate are felt worldwide. An increased number of extreme weather and climatic disasters have occurred during the past 30 years, including droughts, floods, heat waves, and sand storms. These extreme disasters are often related to the onset of ENSO events; therefore, ENSO prediction is very important. However, the forecasting of ENSO events is still hampered by large uncertainties (Li, 1995; Zhang et al., 2003; Yan et al., 2009), and such forecasting presents a challenging problem for scientists worldwide (Kirtman et al., 2001).

The spring predictability barrier (SPB) phenomenon is one of the important causes of prediction uncertainties in ENSO forecasting. The so-called SPB is a phenomenon often experienced by most ENSO-forecasting models, and it is characterized by an apparent drop in prediction accuracy during April and May (Webster and Yang, 1992; Webster, 1995). Real-time forecast results conducted by National Centers for Environmental Prediction (NCEP) and The European Centre for Medium-Range Weather Forecasts (ECMWF) indicate that the SPB still severely affects the forecasting accuracy for ENSOs. Therefore, the SPB problem should be the subject of an in-depth exploration.

Several studies have explored the SPB phenomenon (Webster and Yang, 1992; Webster, 1995; Mu et al., 2007a, b) and have obtained significant results, but debate continues regarding the origin of the SPB. Webster and Yang (1992) suggested that the SPB is caused by rapid seasonal transition of monsoon circulation during the boreal spring. This transition perturbs the Pacific's basic state during a time when the east-west sea surface temperature (SST) gradient is the weakest. Lau at al. (1996) demonstrated that monsoon intensity is closely related to the SPB. Torrence and Webster (1998) showed that the strength of the SPB depends on the degree of phase-locking of the ENSO to the annual cycle. Samelson and Tziperman (2001) demonstrated that the SPB is an inherent characteristic of ENSO forecasting. However, Zheng and Zhu (2010) suggested that reasonable considerations of model errors during the ensemble forecasting process can alleviate the SPB effect, while Chen et al. (1995, 2004) suggested that improving model initialization could reduce this predictability barrier. In any case, the SPB's cause is still elusive.

Recently, using Conditional Nonlinear Optimal Perturbation (CNOP; Mu et al., 2003; Mu and Duan, 2003) and the intermediate-complexity Zebiak-Cane Model (Zebiak and Cane, 1987), Mu et al. (2007b) and Duan et al. (2009) investigated the SPB for El Niño events. They showed that CNOP-type errors can be considered one of the candidate errors that cause a significant SPB. Moreover, Yu (2009) demonstrated that the occurrence of the SPB depends on El Niño events themselves. However, these results were obtained by using theoretical El Niño events generated by the ENSO model. Furthermore, due to a limitation of the model adopted by Yu (2009), they did not investigate La Niña events. Therefore, a natural extension of the work by Yu (2009) would be to explore their method's utility for actual ENSO predictions. Simi-

Corresponding author: DUAN Wan-Suo, duanws@lasg.iap.ac.cn

larly, it is important to explore the SPB associated with La Niña events.

This paper presents our investigation of the seasonally dependent evolution of prediction errors for actual ENSO events. Here we used SST data predicted by a fully coupled ocean-atmosphere model named "FGOALS-g" (Yu et al., 2007). The remainder of this paper is organized in the following way: the data and methods are introduced in Section 2. The SPB phenomenon for the observed ENSO events is explored in Section 3 and Section 4. Finally, the main results are summarized and discussed in Section 5.

2 Data and method

The data used in this study are the SST components predicted by the FGOALS-g model developed at the State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG), Institute of Atmospheric Physics, Chinese Academy of Sciences. Yan et al. (2009) illustrated that this model had a high forecasting accuracy in hindcast experiments that examined the ENSO events between 1982–2007. In the hindcast experiments, the start-months of the predictions were January, April, July, and October for the years 1982–2007. Each prediction used a leading time of 12 months. The predicted SSTs used in our study were ensemble predictions with ten initial conditions that were generated by the SST-nudging approach. The time scale for the SST-nudging term was two days (Yan et al., 2009). Between 1982–2007, there were five main El Niño events: 1982/1983, 1986/1987, 1991/1992, 1997/1998, and 2002/2003. During the same period, there were four La Niña events: 1984/1985, 1988/1989, 1995/1996, and 1998/1999 (Fig. 1). We investigated the predictability of the SST anomaly (SSTA) associated with the ENSO events. Because the 1982/1983 El Niño events predicted by the FGOALS-g model do not include completely both phases

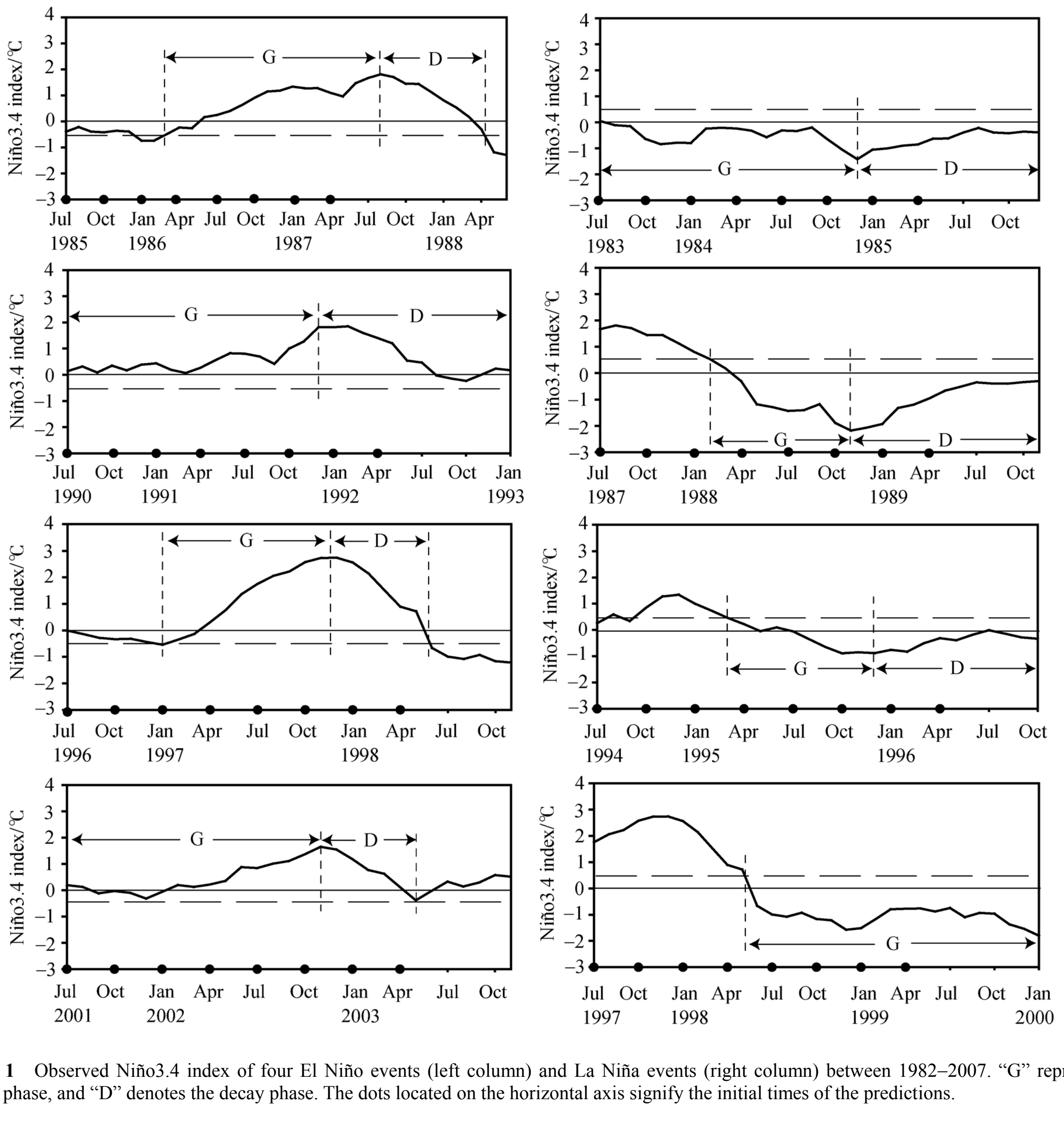

Figure 1 Observed Niño3.4 index of four El Niño events (left column) and La Niña events (right column) between 1982–2007. "G" represents growth phase, and "D" denotes the decay phase. The dots located on the horizontal axis signify the initial times of the predictions.

of El Niño events, we only considered the other four El Niño events and four La Niña events.

The growth phase and decay phase of ENSO events were identified according to the definition provided by Liu et al. (2008). The growth phase was defined as the period during which the Niño3.4 index (i.e., the averaged SSTA over the Niño-3.4 region (170–120°W, 5°S–5°N) changes from a value greater than −0.5°C to the El Niño event's peak value. For La Niña events, the growth phase was defined as the period when the Niño3.4 index changes from a positive value smaller than 0.5°C to the La Niña event's peak value. Similarly, the decay phase of an El Niño event was defined as the period when the Niño3.4 index changes from the peak value to a negative value that is greater than −0.5°C. For a La Niña event, the decay phase was defined as the period when the index value changes from its peak to a positive value that is smaller than 0.5°C. In this context, we use Year (0) to denote the year when the El Niño event attains a peak value. The notations Year (−1) and Year (1) signify the years before and after Year (0), respectively. The El Niño predictions with a start-month of July (−1) (i.e., July in Year (−1)), October (−1), January (0), and April (0) encompass the spring of the El Niño event's growth phase, while the predictions starting with July (0), October (0), January (1), and April (1) encompass the spring of the event's decay phase. For convenience, we denote these predictions as "growth-phase predictions" and "decay-phase predictions", respectively. The La Niña events are similarly signified by the aforementioned signs. Additionally, we analyzed the seasonal dependence of the SSTA forecasting accuracy during the neutral years between 1982–2007. Here, we use Year (0) to denote the neutral year itself, and we use Year (−1) to denote the year before Year (0).

The prediction error for the SSTA was determined by

$$\|T'(\tau)\| = \sqrt{\sum_{i,j}(T'_{i,j}(\tau))^2}.$$

In this expression, $T'_{i,j}(\tau)$ represents the prediction error for the SSTA at time τ, and (i, j) is the grid point in the domain of the Niño3.4 region. This region has a latitude and longitude ranging from 5°S to 5°N and from 170°W to 120°W, respectively. The calendar year was divided into four seasons defined as January to March (JFM), April to June (AMJ), July to September (JAS), and October to December (OND). Next, the slope of $\gamma(t)=\|T'(t)\|$ during different seasons was evaluated. The slope of $\gamma(t)$, denoted by κ, indicates the seasonal growth rate of the prediction error during different seasons. A positive (negative) value of κ implies an increase (decrease) in the error, and larger absolute values of κ indicate more rapid increases (decreases) in the error.

To apply the above strategy to studying the seasonally dependent evolution of prediction errors, it was necessary to derive the SST anomalies (SSTA) from the SST that was predicted by the FGOALS-g model. By calculating the mean values of the SST for each month between 1982–2007, we obtained the annual cycle of the model outputs. We then subtracted the model annual cycle from the predicted SSTs to obtain the time series of predicted SSTAs. Using the predicted SSTAs and the observed SSTAs, we estimated the seasonal growth rate of SSTA prediction errors for ENSO events. The observed SSTAs were taken from NOAA's Optimum-Interpolation monthly SST data, which had a resolution of 1°×1°. This resolution was the same as that of the predicted SST data.

3 The SPB phenomenon exhibited by El Niño predictions generated by the FGOALS-g model

We used the strategy defined in Section 2 to study the SPB of the four El Niño events between 1982–2007. For each El Niño event, the predictions with a leading time of 12 months and with a start month of July (−1), October (−1), January (0), or April (0) encompassed the boreal spring of the El Niño event's growth phase. Those with a start-month of July (0), October (0), January (1), or April (1) encompassed the spring of the event's decay phase (except for the 1986/1987 event). By evaluating the seasonal growth rates of prediction errors in the growth-phase and decay-phase predictions for El Niño, we can explore the dependence of the SPB on the El Niño events' phases. To achieve this comparison, we estimated the growth rates of prediction errors in different seasons by computing the slope of $\gamma(t)$.

Tables 1–4 list the seasonal growth rates (i.e., the slope, κ) of prediction errors for the four El Niño events for the start-months of July (−1), October (−1), January (0), and April (0), respectively. These predictions encompassed the spring of the El Niño event's growth phase. For the start-months of July (−1), October (−1), and January (0), the prediction errors tended to have their largest growth rates during the AMJ season (i.e., in the spring season and the beginning of the summer). They also exhibited significant seasonally dependent evolution for the El Niño events, except for the 1986/1987 event. These results suggested the presence of a significant SPB. When the start-month was April (0), the predictions started directly in the spring, and the largest error growth was during the JAS season. This behavior resulted in a relatively weak SPB.

Mu et al. (2007a) demonstrated that the SPB may result from the combined effects of annual climate cycles, El Niño events themselves, and initial error patterns. The 1986/1987 El Niño event did not phase-lock with the annual cycle. In other words, the peak of the 1986/1987 El Niño event did not occur at the end of the year, and the transition from the cold phase to the warm phase did not occur in the spring. This behavior may be the reason that the evolution of prediction error for the 1986/1987 event did not exhibit an SPB.

We also calculated the seasonal growth rates of prediction errors in ten members of the ensemble prediction. If the prediction errors exhibited the largest growth rates in the AMJ season or JAS season, then our criteria stated that the SPB phenomenon occurred (Mu et al., 2007b). Statistical results showed that when the start-month was July (−1), there were 40 predictions for the 4 El Niño

Table 1 The error growth rates, κ of El Niño predictions when using a start month of July (−1). Bold denotes seasons when the error growth is considerable.

El Niño event	JAS	OND	JFM	AMJ
1986/1987	**14.0340**	1.4535	−8.3007	−5.1289
1991/1992	0.2062	5.3475	−7.7486	**9.3245**
1997/1998	−2.5856	4.1737	0.1718	**23.4215**
2002/2003	0.6974	−0.4389	−4.3018	**8.9090**
Average	3.0880	2.6340	−5.0448	**9.1315**

Table 2 The error growth rates, κ of El Niño predictions when using a start month of October (−1). Bold denotes seasons when the error growth is considerable.

El Niño event	OND	JFM	AMJ	JAS
1986/1987	**16.8278**	−1.3579	−6.8903	−11.4712
1991/1992	5.0105	−9.1463	**11.4121**	−5.9407
1997/1998	7.4019	1.8187	**18.6503**	5.2591
2002/2003	−6.9819	−2.8243	**11.1919**	5.7322
Average	5.5646	−2.8775	**8.5910**	−1.6052

Table 3 The error growth rates, κ of El Niño predictions when using a start month of January (0). Bold denotes seasons when the error growth is considerable.

El Niño event	JFM	AMJ	JAS	OND
1986/1987	**5.9383**	−0.1348	−8.4775	3.2421
1991/1992	4.3690	**15.2974**	−19.0510	9.7095
1997/1998	3.9641	**16.6585**	−5.5901	−2.7767
2002/2003	2.9354	**22.3728**	−7.7936	−0.8049
Average	4.3017	**13.5485**	−10.2281	2.3425

Table 4 The error growth rates, κ of El Niño predictions when using a start month of April (0). Bold denotes seasons when the error growth is considerable.

El Niño event	AMJ	JAS	OND	JFM
1986/1987	−1.7912	−0.4495	1.3655	**2.3603**
1991/1992	4.2199	**7.9869**	3.9446	4.3627
1997/1998	2.4936	−4.6787	0.6526	**5.1513**
2002/2003	1.1134	**16.1475**	−7.4086	−2.7939
Average	1.5089	**4.7516**	−0.3615	2.2701

events, and 31 of those predictions exhibited the SPB phenomenon. The proportion of the ensemble predictions exhibiting an SPB was 77.5%. Similarly, those percentages corresponding to the start-months of October (−1), January (0), and April (0) were 77.5%, 72.5%, and 60%, respectively. These data indicated that for El Niño prediction models starting in July (−1), October (−1), and January (0), the SPB phenomenon was present. For models starting in April (0), the SPB was not obvious. Therefore, the El Niño growth-phase predictions tended to cause a prominent SPB, and the predictions with a start month of April (0) exhibited a less prominent SPB than those using other start months. We conclude that the SPB may be an essential characteristic of ENSO predictions.

For the start months of July (0), October (0), January (1), or April (1), the El Niño predictions encompassed the spring of the El Niño event's decay phase (except for the 1986/1987 event); these models represent the decay-phase predictions. By estimating the error growth rates, we found that when the start-month is July (0), the largest error growth rates of the three El Niño events occurred in the OND, AMJ and JAS season, respectively. On the other hand, for the start-month of October (0), the largest error growth rates occurred in the OND season. For the start-months of January (1) and April (1), the prediction errors exhibited the largest growth rates in the either AMJ season or the OND season. Regardless, for the El Niño decay-phase predictions, the largest error growth rates did not always occur during the spring season. In other words, the decay-phase predictions of El Niño events did not present an obvious seasonally dependent evolution of prediction errors. Thus, these predictions exhibit a weak SPB.

Ten of the ensemble predictions encompassed the spring of the El Niño event's decay phase, and the seasonal growth rates of these members' prediction errors were also investigated. For the start-months of July (0), October (0), January (1), or April (1), the proportion of the predictions exhibiting an SPB was small compared to that of the growth-phase predictions exhibiting an SPB. Furthermore, the decay-phase predictions exhibited a weaker SPB than the other members of the ensemble predictions. In other words, by using an ensemble forecast with different initial conditions, the SPB phenomenon could be reduced. This result indicated that the SPB is closely related to the uncertainties of the initial conditions. However, the SPB phenomenon in the decay-phase predictions was less prominent than in the growth-phase predictions. These results also imply that the SPB phenomenon was related to the ENSO events themselves.

4 The SPB phenomenon exhibited by La Niña predictions generated by the FGOALS-g model

Section 3 described how El Niño growth-phase predictions tended to exhibit a prominent SPB, while the decay-phase predictions had a less significant SPB. In this section, we describe our investigation of the SPB phenomenon for the La Niña predictions performed using the FGOALS-g model. The definitions of growth phase and decay phase for each La Niña event were similar to those used for El Niño events (except for the 1998/1999 event).

We studied the seasonally dependent evolution of prediction errors for the four La Niña events that occurred between 1982–2007. There was not a significant SPB for the growth-phase predictions of La Niña events. However, the decay-phase predictions with a start-month in January (1) exhibited a prominent SPB. The predictions with a start-month of July (0), October (0), or April (1) did not present an obvious seasonally dependent evolution of prediction errors. Thus, these models did not exhibit a significant SPB. Tables 5–8 list the corresponding seasonal growth rates of prediction errors. For the 1998/1999

Table 5 The error growth rates, κ of La Niña predictions when using a start month of July (−1). Bold denotes seasons when the error growth is considerable.

La Niña event	JAS	OND	JFM	AMJ
1984/1985	−1.7720	−8.1956	**21.1823**	−1.3639
1988/1989	**19.6745**	−5.2589	−5.8381	1.4092
1995/1996	−1.2286	**6.6341**	−8.2167	−3.6610
1998/1999	−1.6310	10.0125	11.1387	**22.3826**
Average	3.7607	0.7980	4.5666	**4.6917**

Table 6 The error growth rates, κ of La Niña predictions when using a start month of January (0). Bold denotes seasons when the error growth is considerable.

La Niña event	OND	JFM	AMJ	JAS
1984/1985	**20.6852**	−5.9568	−15.9025	−2.1503
1988/1989	0.8015	**3.0969**	0.1765	2.3241
1995/1996	**11.9307**	7.0700	−14.2091	−3.4893
1998/1999	0.3520	2.2753	8.9794	**10.3351**
Average	**8.4424**	1.6214	−5.2389	1.7549

Table 7 The error growth rates, κ of La Niña predictions when using a start month of July (0). Bold denotes seasons when the error growth is considerable.

La Niña event	JAS	OND	JFM	AMJ
1984/1985	3.8322	**28.6102**	−7.5550	−5.9142
1988/1989	−1.7241	**2.6647**	−5.7061	0.2726
1995/1996	**4.8980**	−5.0450	0.8937	1.1813
Average	2.3354	**8.7433**	−4.1225	−1.4868

Table 8 The error growth rates, κ of La Niña predictions when using a start month of January (1). Bold denotes seasons when the error growth is considerable.

La Niña event	JFM	AMJ	JAS	OND
1984/1985	−6.5301	−0.6698	**5.2977**	5.0982
1988/1989	−1.0639	2.7201	**17.1540**	5.5175
1995/1996	−5.3403	−1.8484	**16.8388**	8.1510
Average	−4.3114	0.0673	**13.0968**	6.2556

La Niña event, the predictions starting in July (0), October (0), January (1), or April (1) did not encompass the spring of the event's decay phase, so we did not consider the 1998/1999 La Niña event for this investigation.

Finally, we investigated the error growth for predictions made for the neutral years. For the start-months of July (−1), October (−1), January (0), and April (0), the largest error growth rate did not always occur in the spring season, and there was not a significant SPB. Tables 9−10 list the seasonal growth rates of prediction errors for the SSTA during the neutral years.

We conclude that there was not a significant SPB for the growth-phase predictions of La Niña events. Nevertheless, for the decay-phase predictions, the SPB was prominent when using a start-month of January (1). The SPB was not prominent when using a start-month of July

Table 9 The error growth rates, κ of neutral events predictions when using a start month of October (−1). Bold denotes seasons when the error growth is considerable.

Neutral year	OND	JFM	AMJ	JAS
1990	9.1535	−2.6995	**13.6756**	−2.2380
1994	**12.3763**	−0.7383	2.6898	−2.3225
2001	7.8238	−1.8619	−3.0502	**10.1400**
2004	**8.0981**	4.2522	3.5523	−4.0718
Average	**9.3629**	−0.2619	4.2169	0.3769

Table 10 The error growth rates, κ of neutral events predictions when using a start month of January (0). Bold denotes seasons when the error growth is considerable.

Neutral year	JFM	AMJ	JAS	OND
1990	8.4099	−9.1663	**15.4307**	9.3494
1994	4.0764	11.2355	−9.0167	**16.7961**
2001	4.6665	−1.9569	11.0587	**13.8308**
2004	2.7314	**6.5129**	−5.4735	−0.2478
Average	4.9711	1.6563	2.9998	**9.9321**

(0), October (0), or April (1). Although an SPB was observed in La Niña predictions, it was relatively weak compared to the SPB observed in El Niño predictions. Additionally, when using the FGOALS-g model, the SPB did not occur in predictions of the SSTA during neutral years.

5 Summary and discussion

Using SST predicted for the equatorial Pacific Ocean by the FGOALS-g model, we investigated the seasonal dependence of prediction errors for ENSO events. Our results suggested that for El Niño growth-phase predictions, the prediction errors tend to have their largest growth rate in the AMJ or JAS season, and they exhibit a significant seasonally-dependent evolution. For El Niño decay-phase predictions, the occurrence of the SPB phenomenon depends on the identity of the prediction's start month. In summary, the SPB observed for the growth phase of El Niño events is much more prominent than that for the decay phase. This conclusion is in accordance with the results of Mu et al. (2007a, b). Furthermore, For La Niña events and neutral years, the SPB for both growth-phase and decay-phase predictions is less prominent than those for the El Niño events. We conclude that the SPB phenomenon depends remarkably on the ENSO events themselves. Additionally, we demonstrate that the ensemble predictions of ENSO events exhibit a weaker SPB phenomenon than the ensemble members with different initial conditions. This result indicates that the occurrence of the SPB is also related to the predictions' initial uncertainties.

The SPB is a challenging, unresolved problem. In this paper, we do not distinguish initial errors from model errors, and we demonstrate that when using the FGOALS-g model, the El Niño predictions exhibit a significant SPB. Furthermore, Mu et al. (2007b) only considered the role of initial errors and demonstrated that the El Niño predictions exhibited a significant SPB when using the Zebiak-Cane model. They further suggested that initial errors might play an important role in the SPB for El Niño events. Therefore, future inquiries should investigate the following: the role that model error plays in causing an SPB phenomenon in ENSO predictions, the relative influence of initial error and model error on the SPB, and the use of theoretical results to reduce the SPB in realistic predictions and to improve the ENSO forecasting accuracy. All of these problems still require further in-depth study.

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